Research Article

Reduced switches multilevel inverter integration with boost converters in photovoltaic system

Yatindra Gopal[1] · Dinesh Birla[1] · Mahendra Lalwani[1]

Abstract

Multilevel inverters (MLIs) are developed to meet medium voltage and high power applications in flexible power systems. The conventional configuration of multilevel inverter requires more switches and has limitation to its wide range application. This paper reports the performed work on 1-phase 7-level reduced switch multilevel inverter (RS MLI) in photovoltaic (PV) system. RS MLI configuration integration with PV system which uses less number of switching components for specified number of voltage output levels as compared to that of conventional multilevel inverter topology. To performed enhanced operation of PV cells and maximize the solar energy extraction an incremental conductance based maximum power point tracking scheme is used. To improve the quality of RS MLI output parameters mainly total harmonic distortion and switching losses, selected harmonic elimination based genetic algorithm method is consider for control the gating pulse of PV based RS MLI. This work is performed using MATLAB/SIMULINK software.

Keywords Reduced switch multilevel inverter (RS MLI) · Maximum power point tracking (MPPT) · Incremental conductance (IC) · Genetic algorithm (GA) · Total harmonic distortion (THD)

1 Introduction

Due to conventional energy production shortage of fossil fuels and environmental problems caused by, solar power has become most popular. To meet the modern time solar-electric-energy generation is consistently growing by 20–25% (percent) per year over the past 20 years [1]. Photovoltaic (PV) devices produce electric power directly from sunlight by an electronic method that occurs naturally in certain types of material, called semiconductors. The semiconductor device that transforms solar light in form of electrical energy is termed PV cell, and the phenomenon is named as 'PV effects'. The size a solar PV array, cells are mounting up in structure of series–parallel formation for mandatory energy. The voltage outputs of PV arrays vary with change in irradiation and environmental changes. Therefore a MPPT control technique with boost

converter is taken to produce the maximum voltage from PV array. In recent years, various control techniques have been proposed for tracking the maximum power point (MPP). Perturbation and observation (P&O) technique is broadly used in the MPPT controllers owing to its simplicity and easy execution. P&O is work based an iterative technique in this operating point at regular interval is perturbed and it thus oscillates around the point $dP/dV = 0$ i.e., MPP. Incremental conductance (IC) technique has been used to enhance the tracking accuracy and dynamic performance when quickly change in atmospheric environment [2]. It can identify when the MPPT reaches the MPP and stops process of perturbing the operating point to track quickly decreasing and increasing irradiance conditions with superior precision than P&O technique. In this work, a novel IC MPPT method is used with the adaptive variation of step size. An adjustment coefficient is adopted

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to regulate the step size. Therefore, the PV system can keep a large step size when the operating point is far from the MPP and a decreasing step size when the operating point is close to the MPP, even under extreme irradiance change [3]. IC MPPT method can effectively solve the problem of traditional method not taking into account the stability and dynamic response speed simultaneously when the irradiance changes tremendously. Compared with other variable step size methods, the proposed method also has less complex adjustment coefficient and computation to improve the computing speed [4].

The obtained voltage output from PV arrays is less as compared to the voltage rating of most other networks, hence a DC–DC boost converter is used. Basically the output voltage of PV array with boost converter is DC and for commercial purposes it needs to be converted into AC form because most of the loads are AC. MLIs acts main function in PV system to convert the produced DC voltage to AC voltage, to be fed into the load.

Various conventional topologies of MLIs are used for conversion of DC to AC such as neutral point clamped MLI (NPC MLI), flying capacitor MLI (FC MLI) and cascaded H-bridge MLI (CHB MLI) [5, 6]. NPC MLI requires more no. of diodes and the no. of capacitors requires in the FC MLI is more because of voltage balancing requirement. The traditional NPC MLI is integrated with PV system, but voltage across each capacitor needs to be maintained and an external controller is required for this Panda et al. [7]. CHB MLI is suitable for PV panels but it requires more no. of PV panels in series or parallel connection when the no. of levels increases. Therefore no. of switches of CHB MLI increases when the level of inverter increases. The no. of switches in MLI defines cost, the size of the circuit, reliability and complexity. So the key element in designing MLI is the no. of switches required against the required voltage level. To obtain the same output obtained as in a 7-level CHB MLI, a new circuit topology has been developed with reduced no. of switches without increasing the no. of H-bridges [8].

SHE technique solves different non-linear equations and gives better optimal results for MLIs [6]. In the work reported in this present manuscript, the "selected harmonic elimination" (SHE) technique is used to reduce selected lower harmonics such as 5th and 7th from the voltage output of MLIs. Furthermore, this paper reports the work on PV based reduced switch 7-level MLI topology, which using less switches, requires less no. of devices involves less expenditure and still RS MLI produces same voltage output as produced by CHB MLI and.

Investigations [9] have explained different methods to reduce harmonics using pulse width modulation (PWM) technique and selected harmonic elimination (SHE) method. Lower-order harmonics are dominant in nature and complete elimination of these harmonics is not possible using conventional PWM techniques. SHE also called programmed PWM technique approach is thus used to eliminate selected harmonics by calculating optimal switching angles [10]. Switching angles are calculated by solving transcendental non-linear equations. Iterative methods such as Newton–Raphson (NR) method [11] and mathematical resultant theory method suffer from some disadvantages. The former approach requires good initial guess and gives only a few sets of solution. The degree of polynomial becomes large when the later approach is applied to higher level asymmetrical MLIs as the no. of harmonics to be eliminated increases. Active harmonic elimination (AHM) technique is a further combinational method of NR and resultant theory method for reducing any no. of selected harmonics. However, AHM technique doesn't find satisfactory possible solution for the infeasible modulation index. Thus, bio inspired optimization method such as GA (Genetic Algorithm) based selected harmonic elimination is used in this paper to improve the system robustness as suggested in Sen et al. [12] and Madhusudhana et al. [13].

GA is competent for solving constrained and unconstrained optimization problems based on proper selection of original population and progressively frequently modify this individual population for solutions [14]. By GA, obtaining optimized switching angles of PV based 7-level RS MLI, this work attempts to obtain minimum THD.

This paper proposes a 1-ϕ RS MLI integrated with photovoltaic panel. The objective of the proposed RS MLI is to increase the output voltage level with reduced the no. of switches. A novel IC MPPT technique with DC–DC boost converter is utilized for replacing each DC input of proposed RS MLI. The utilization of separate DC–DC converter is by eliminating the extra controller to balance the DC link voltage.

The organization of paper description is follows: Sect. 2 describes the structure and modeling of PV panel. Section 3 shows the configuration of DC–DC boost converter to sustain the stable load voltage between the PV array and inverter. To understand the need of Novel IC based MPPT technique to generate maximum power from the PV panel is described in Sects. 4. 1-ϕ PV integrated RS MLI configuration with its different operating mode and its switching schemes are described in Sects. 5 and 6, respectively. Selective harmonic elimination (SHE) technique is described in Sect. 7. Section 8 describes the GA

based optimization technique to achieve the best possible values of switching angles by SHE technique. Results obtained using IC MPPT with DC–DC boost converter, without DC–DC boost converter and PV based 7-level RS MLI voltage output with reduced total harmonic distortion are presented in Sect. 9. Section 10 describes the conclusion of this paper.

2 Modeling of PV cell

Renewable source of energy suggest various motivation such as incurring no cost of fuel, pollution free, requires less maintenance and has noise less emission [18]. Semiconductor device based PV cell is used, that converts sunlight to electrical energy through photovoltaic effect. Nowadays PV arrays mostly used are in standalone application or grid connected. A PV array consists of series and parallel connection of PV cells. Series relation are accountable for increase the voltage of modules whereas the parallel accountable is responsible for increase the current in the array. Generally a solar cell can be modeled by a current source and an inverted diode connected in parallel to it. It has own series and parallel resistance. Series resistance is due to hindrance in the path of flow of electron from n to p junction and parallel resistance is due to the leakage current. Based on single diode modeling of PV cell configuration is used in this work due to simplest and less complex. The efficiency of PV modules is low due to their non-linear and temperature dependent voltage-current and voltage–power characteristics, due to non-linear characteristic of voltage and current and distinct MPP [15, 16]. The equation of ideal PV cell for generating I–V characteristic is defined as under:

$$I = I_{PV,cell} - I_d \tag{1}$$

$$I_D = I_{0,cell}\left[\exp\left(\frac{cV}{akT}\right) - 1\right] \tag{2}$$

Here, $I_{PV,cell}$ represents the current produced by solar cell and $I_{0,cell}$ is reverse saturation current. I_D Indicates the equation of shockley diode. c, k, a and T represent the electron charge ($1.60217646 * 10^{-19}$ C), Boltzmann constant ($1.3806503 * 10^{-23}$ J/K), constant of diode ideality and absolute temperature, respectively. I_0 and I_{PV} represent the saturation current of array and photovoltaic current respectively. The PV array is made by PV cell which is connected in parallel or series configuration. The connection of solar cells in parallel, gives higher current whereas in
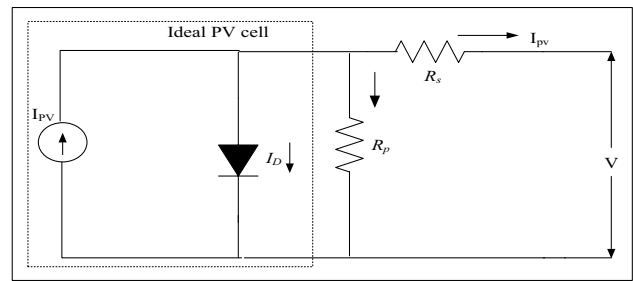

Fig. 1 The identical equivalent circuit of PV cell in single diode structure

series provides higher output voltage. Figure 1 represents the comparable circuit of PV cell in single diode structure.

By far, the simplest approach is the single diode model i.e. a current source in parallel to a diode as shown in Fig. 1 a where the output of the current source is directly proportional to the light falling on the cell. This model only requires three parameters to completely characterize the I–V curve, namely short-circuit current (Isc), open circuit voltage (Voc) and diode ideality factor "a" [16]. In fact, single diode model does not adequately represent the behaviour of the cell when subjected to environmental variation, especially at low voltage. An improvement of this model is done by the inclusion of one series resistance, Rs. This model is known widely as the Rs-model. Due to its simplicity and computational efficiency, the Rs-model is by far the most widely used model in PV system simulation.

Figure 2 shows the I–V and P–V characteristics of PV cell. It is important to mention here that there exists a unique operating point marked as MPP in I–V and P–V curve. At the same time this MPP point keeps shifting its position when any atmospheric change occurs. Since per watt cost of solar PV and installation cost are higher; it forced PV system to operate the PV panel at MPP.

The mathematical formula for generating I–V characteristic of a practical PV cell is as follows [16].

$$I = I_{PV} - I_0\left[\exp\left(\frac{V + R_S I}{aV_t}\right) - 1\right] - \frac{V + R_S I}{R_P} \tag{3}$$

where, $V_t = \dfrac{V_S kT}{c}$ and $I_{PV} = \left(I_{PV,n} + K_1\Delta_t\right)\dfrac{r}{r_n}$ (4)

$$I_0 = \frac{I_{SC} + K_I\Delta_t}{\exp\left[\left(V_{OC,n} + K_V\Delta_t\right)/aV_t\right] - 1} \tag{5}$$
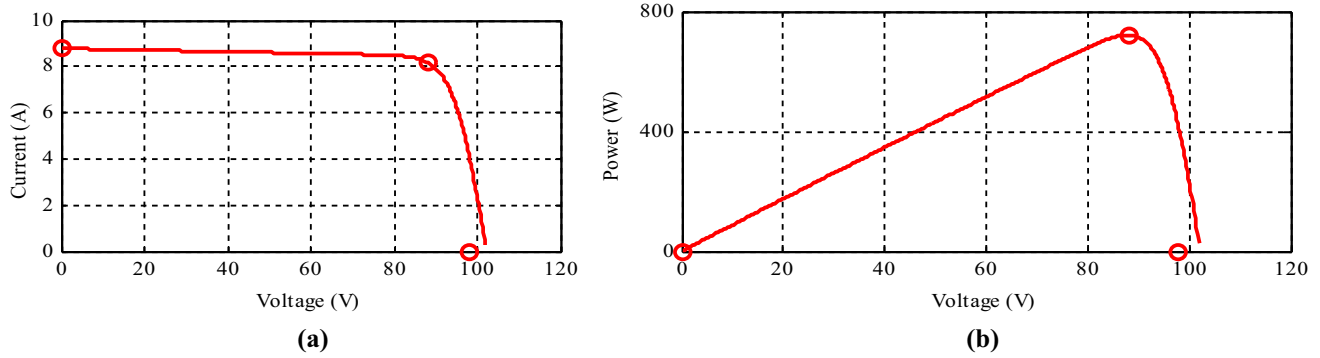
Fig. 2 **a** I–V characteristics curve of PV cell, **b** P–V characteristics curve of PV cell

Here, $I_{PV,n}$ indicates the nominal value of PV cell output current. R_P and R_S represent parallel and series solar resistance, respectively. V_t symbolize the thermal voltage, $V_{OC,n}$ and $I_{SC,n}$ denotes the voltage of open circuit and value of nominal current, respectively. K_V and K_I indicates the voltage of short circuit and current coefficient, respectively. r and r_n indicate the irradiation of device surface and nominal irradiation. Δ_t indicates the difference between normal temperature and actual temperature.

3 DC–DC boost converter configuration

To sustain the stable load voltage a DC–DC boost converter is used between the PV array and inverter [17]. It plays a key role in PV application because produced voltage from the PV system is not sufficient to meet the load requirement. In this work, DC–DC boost converter produced maximum power by novel MPPT technique and fed into the input of RS MLI. MPPT technique generate duty cycle for the converter switch and work at high switching frequency to produce maximum power from PV panels. If the converter operates at continuous conduction mode, the inductor current never falls to zero [16]. The formulas for duty cycle, inductor (L) and capacitor (C) are given in the below equations.

$$\frac{V_{out}}{V_{in}} = \frac{1}{1-D} \tag{6}$$

$$\text{Inductor}\,(L) = \frac{V_{in} \times D \times T}{\Delta_{iL}} \tag{7}$$

$$\text{Capacitor}\,(C) = \frac{V_{out} \times D}{R \times \Delta V_{out} \times f} \tag{8}$$
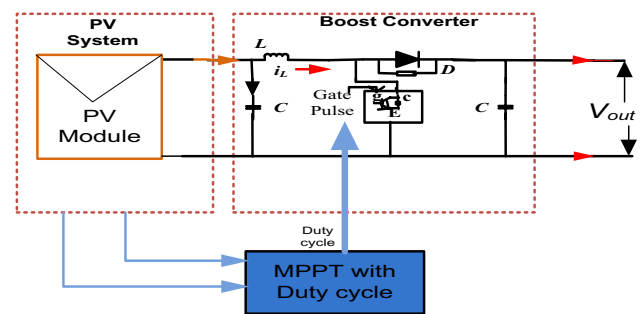

Fig. 3 System configuration for PV with MPPT technique and DC–DC boost converter

where D is duty cycle, V_{in} and V_0 are input and output voltage of boost converter and DV_0 represents capacitor voltage. When D increases from 0 to 1, then output is more than input voltage. Figure 3 shown the concept of PV integrated with DC–DC boost converter and MPPT technique to offer optimal duty cycle of boost converter with PV.

When PV array is combined with boost converter, it is examine that with increase the duty cycle, average current of PV array also increases and a PV array output voltage decrease. Therefore raising the D, results in movement of the operational point to the left of the PV array V–I characteristic. Similarly decrease in the D results in decrease in PV array average current and PV array output voltage increases. It results in operating point changing to the right of PV array. Incremental conductance (IC) MPPT technique is used to automatically vary the value of D for DC–DC converter to produced stable DC voltage at RS MLI terminal.

4 IC based MPPT technique

In order to reduce the undesirable effect of the mismatches and to improve the performance of the PV system, the PV cell must be work at different voltages to get better the utilization per PV module [18]. The separate DC links in the RS MLI make independent control of voltage possible. In this paper present in the work IC MPPT technique is used to generate maximum power from PV array and to obtained good performance even with changes in environmental condition. By using IC MPPT technique, generated duty cycle it used for triggering the DC–DC boost converter. The incremental conductance method [19], which is based on the fact the slop of the PV array power versus voltage curve is zero at the MPP, has been proposed to improve the tracking accuracy and dynamic performance under rapidly varying conductions [4]. In literature [20] work is carried out to compare the dynamic performance of two well accepted MPPT techniques i.e. P&O and IC when tested using the EN 50530 Test. Both methods are widely used in existing PV system; hence their performance under rapid changes of weather will gives a clear picture about the robustness of these MPPT techniques. And it can also implement these practically; a DC–DC converter is configured as MPPT control structure. In Ishaque et al. [20] dynamic test profile for the EN 50530 standard that is used to evaluate the effectiveness of any MPPT methods. The study state oscillations would be eliminated in theory since the derivative of the power with respect to the voltage vanishes at MPP. The mathematical expression of IC technique is as follows:

$$\text{Power}\,(P) = V \times I \tag{9}$$

$$\frac{dP}{dV} = 1 + V\frac{dI}{dV} \tag{10}$$

$$\frac{dP}{dV} = 0\ (\text{At MPPT}) \tag{11}$$

$$\frac{dI}{dV} = -\frac{1}{V} \tag{12}$$

where dI/dV: Incremental conductance, I/V: Instantaneous conductance. Equation (12) indicates that MPP can be originating by comparing instantaneous conductance to the incremental conductance. The process of this algorithm is work in three different zones and is shown in Table 1. The flow chart arrangement of IC technique

Table 1 IC method for MPP

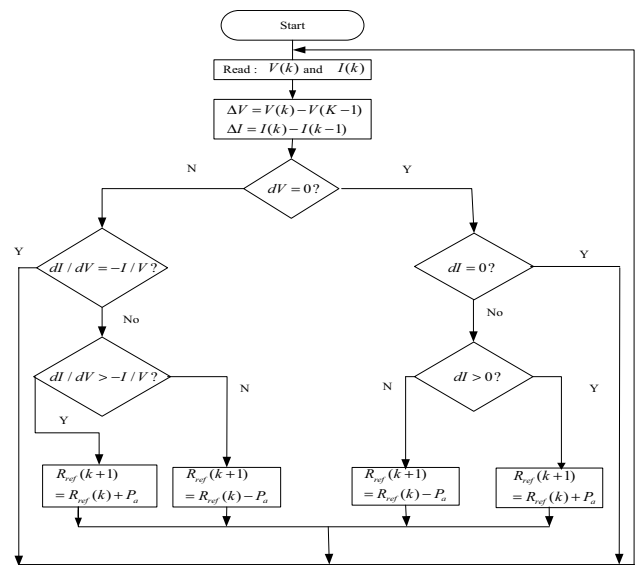| Before MPP	After MPP	At MPP
$\frac{\Delta P}{\Delta V} > 0$ or $\frac{dP}{dV} + \frac{1}{V} > 0$	$\frac{\Delta P}{\Delta V} < 0$ or $\frac{dP}{dV} + \frac{1}{V} < 0$	$\frac{\Delta P}{\Delta V} = 0$ or $\frac{dP}{dV} + \frac{1}{V} = 0$

Fig. 4 Flowchart of the incremental conductance algorithm

is given in Fig. 4. This method is complex and computationally more demanding as compared to P&O technique algorithm.

As shown in Fig. 4. R_{ref} is the reference voltage at which the PV array is forced to operate. At the MPP, R_{ref} equal to Vmpp. Once the MPPT reached, the operation of PV array is maintained at this point unless a change in dI noticed, indicating a change in meteorological conditions and the MPP. The algorithm decrements or increments R_{ref} using a constant adjustment step width (P_a) to track the new MPP [4].

5 Reduced switch multilevel inverter (RS MLI)

The conventional CHB MLI is one of the important topology in the family of MLIs. In CHB MLI all DC sources are considered to be identical since all of them are either fuel cells or PV arrays and batteries etc. [8, 21]. It requires less no. of components as compared to NPC MLI and FC MLI and gives better performance. The significant component in MLIs is switches which define the size of circuit, reliability, area of installation, control complexity and cost. In conventional MLIs when the output voltage level increases, then the size, cost, and volume of inverters also increase. In this paper work, RS MLI is used for provide a large no. of output levels with less switching
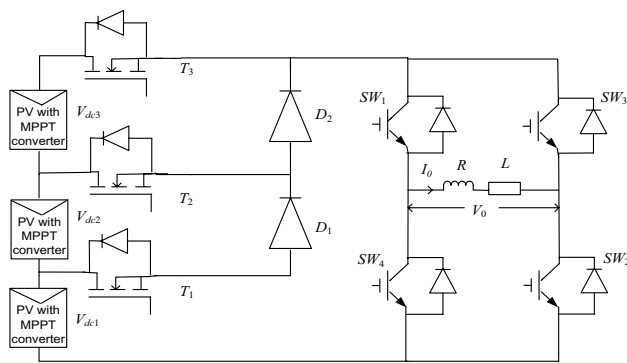
Fig. 5 The proposed structure of 7-level reduced switch multilevel inverter with PV system
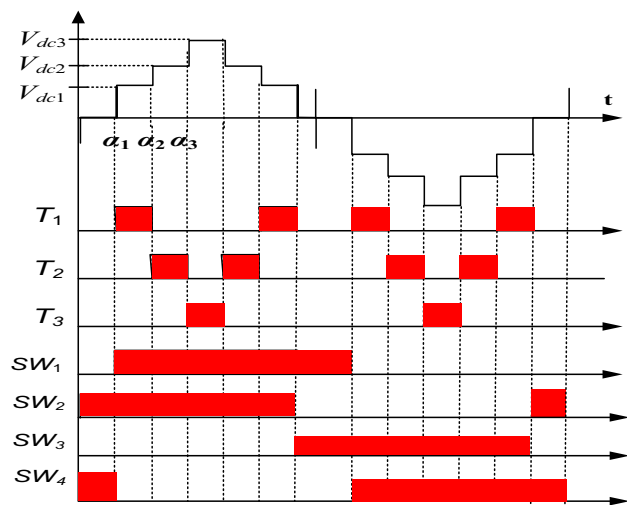

Fig. 6 7-level PV based RS MLI output voltage waveform with corresponding switching states

components and reduced cost. The proposed RS MLI circuit reduces the voltage stress on the switches and enhances the protection from over voltage and dV/dt breakdown consideration. The configuration of PV RS MLI scheme is shown in Fig. 5. Figure 6 shows the

proposed RS MLI output voltage waveform with corresponding switching states. In RS MLI configuration of Fig. 4 seven switches (SW_1–SW_4 and T_1–T_3) with two diodes (D_1 and D_2) are used.

The H-bridge switches (or polarity generation switches) operate at low switching frequency whereas the level generation switches T_1–T_3 operate at high switching frequency. Hence a cost-effective solution is to choose low switching power components for the H-bridge and high switching power components for the level generation. The working principle of RS MLI is summarized in following cases.

Case a T_1 is ON, flow of current is through diode D_1 and D_2, and switches SW_1 and SW_2. The output voltage across the load is $+V_{dc1}$. Correspondingly when SW_3 and SW_4 are switched ON, output voltage across load is $-V_{dc1}$.

Case b Switch T_2 is on in this case, current flows through diode D_2 and switches SW_1 and SW_2. The output voltage across load is $+V_{dc2}$. correspondingly when SW_3 and SW_4 are switched ON, output voltage across load is $-V_{dc2}$.

Case c In this mode T_3 is ON, current flows through SW_1 and SW_2. The output voltage across load is $+V_{dc3}$ and D_1 and D_2 reverse biased. Correspondingly when SW_3 and SW_4 are switched ON, voltage output is $-V_{dc3}$.

Case d In this mode both SW_1 and SW_3 or SW_2 and SW_4 are ON making T_1, T_2 and T_3 OFF, voltage gives zero output across the load.

The Operation of proposed RS MLI for generating different output voltage levels shown in Fig. 6 and corresponding switching scheme of RS MLI is depicted in Table 2. The output power obtained for PV panel[1] without boost converter shown in Fig. 7. From Fig. 7 it can observed the initial oscillation is generate due to change in irradiance and temperature after that constant power produced.

Table 2 Switching schemes of 7-level RS MLI

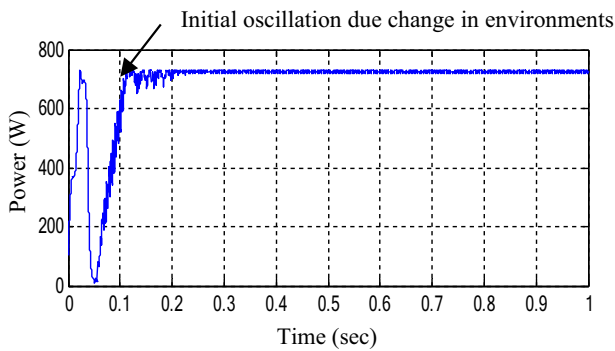| Switching state	T_1	T_2	T_3	SW_1	SW_2	SW_3	SW_4	D_1	D_2
V_{dc3}	OFF	OFF	ON	ON	OFF	OFF	OFF	✕	✕
V_{dc2}	OFF	ON	OFF	ON	ON	OFF	OFF	✕	✓
V_{dc1}	ON	OFF	OFF	ON	ON	OFF	OFF	✓	✓
0	0FF	OFF	OFF	ON	OFF	ON	OFF	✕	✕
0	OFF	OFF	OFF	OFF	ON	OFF	ON	✕	✕
$-V_{dc1}$	ON	OFF	OFF	OFF	OFF	ON	ON	✓	✓
$-V_{dc2}$	OFF	ON	OFF	ON	OFF	OFF	ON	✕	✓
$-V_{dc3}$	OFF	0FF	ON	OFF	OFF	ON	ON	✕	✕

Fig. 7 Output power obtained for PV panel[1] without boost converter

The proposed RS MLI configuration for generating different output voltage levels shows in Fig. 8.

6 Comparison of proposed RS MLI topology with state-of-art topologies

In this section, structure of RS MLI is first compared with the traditional CHB MLI, DC MLI, and FC MLI. Thereafter the comparison is extended taking into account the recently developed MLIs topologies. For creating N_l output voltage levels, the projected RS MLI needs only $(N_l+7)/2$ no. of switches (N_{sw}), however conventional MLI topologies

Fig. 8 Proposed RS MLI configuration for generating different output voltage levels. **a** case a: $+V_{dc}$, **b** case b: 2Vdc, **c** case c: $3V_{dc}$, **d** case d: 0
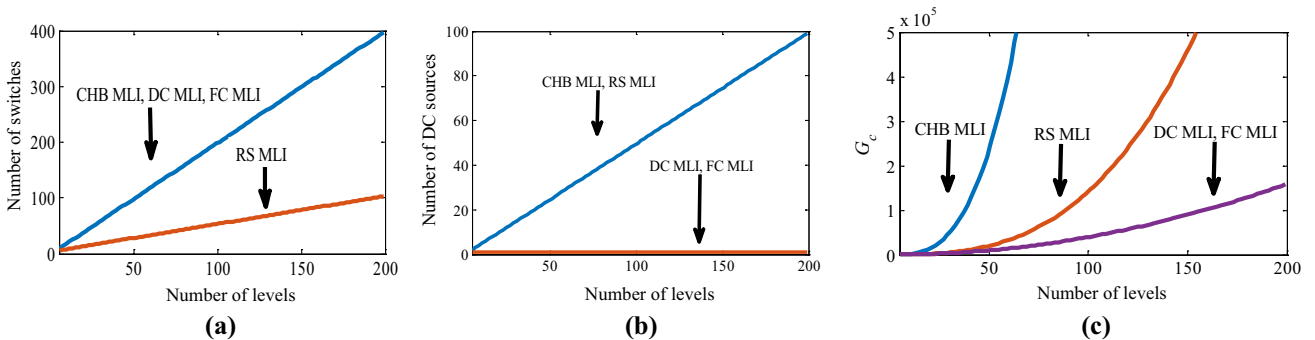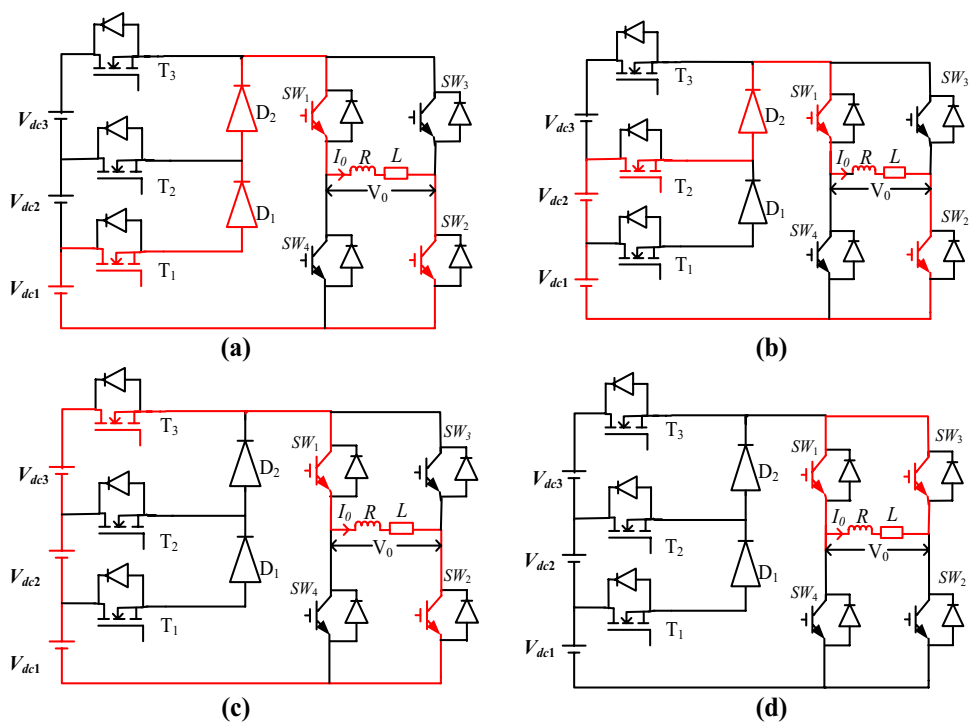

Fig. 9 RS MLI topology comparison with the conventional topologies **a** No. of required switches against the no. of voltage levels, **b** No. of DC voltage sources against the no. of voltage levels, **c** Coefficient G_c variation against the no. of voltage levels

requires $2(N_l - 1)$ switches per phase. N_l is denotes the no. of voltage level at the output. As shown in Fig. 9a, the RS MLI inverter needs fewer switches to appreciate N_l voltage levels at the output. The essential no. of driver circuits (N_{driver}) is equal to N_{sw} for all topologies CHB MLI, DC MLI and FC MLI.

Figure 9b shown the comparison of the no. of DC voltage sources for DC MLI, FC MLI, CHB MLI and RS MLI structures. For appreciating N_l voltage levels, CHB MLI and RS MLI topology needs $(N_l - 1)/2$ voltage sources DC, where DC MLI and FC MLI necessity only one DC source with $(N_l - 1)$ DC bus capacitors. However, the RS MLI structure not need clamping diodes or clamping capacitors like a CHB-MLI. But, DC MLI requires $(N_l - 1) \times (N_l - 2)$ additional clamping diodes per phase and FC-MLI requires $(N_l - 1) \times (N_l - 2)/2$ clamping capacitors per phase.

Here G_c is consider the volume, size, and cost of the MLI. The coefficient G_c can be defined as follows:

$$G_c = N_{DC} \times N_{sw} \times N_{driver} \times N_{vr} \qquad (13)$$

where N_{vr} is the variation of voltage sources DC magnitudes. The symmetrical MLI topologies are occupied for comparison, only one variety of DC source is selected.

Figure 9c indicates the coefficient variation of the G_c with respect to N_l levels of voltage. The structure of CHB MLI has high value of G_c as related to the DC MLI and FC MLI structure. The RS MLI structure has lower value of G_c coefficient than the CHB MLI structure. It is indicating the size and overall cost in designing the RS MLI is reduced than the conventional and other H-bridge based MLI structure. In Fig. 9c the no. of diodes and clamping capacitors are not considered into account when calculating the value of G_c. So, it is lesser for DC MLI and FC MLI structure. But, the total cost of DC MLI and FC MLI structure is more than CHB MLI and RS MLI.

The proposed RS MLI is compared with several recently developed MLI topologies in view of number of switches,

number of diodes, and number of DC sources. More is the number of switches, DC sources, and diodes, more will be the cost of an MLI. Figure 10a shows the proposed RS MLI uses least number of switches compared to the well-known MLIs 'T1' in Chattopadhyay and Chakraborty [22], 'T2' in Lee et al. [23], 'T3' in Samadaei et al. [24], 'T4' in Sun et al. [25], 'T5' in Babaei et al. [26], and 'T6' in Ye et al. [27]. The proposed RS MLI and T6 have identical switch count for all N_l, and due to which these can be a preferred alternative to the conventional MLIs in medium/high voltage applications. The topologies T5, T6, and RS MLI require additional discrete diodes for level generation. For producing N_l output voltage levels, less diodes are needed in the RS MLI, however fewer diodes are required in T5 as shown in Fig. 10b.

Isolated DC sources are usually required to produce the multiple voltage steps at the output. Few MLIs designed based on reducing the DC source count consists of capacitors. Figure 10c shows most of the MLIs require same source count (DC source and capacitors) except the MLIs T1 and T3.

7 PV integrated 1-phase reduced switch multilevel inverter (RS MLI)

The general configuration of PV based 1-phase 7-level RS MLI used in this paper, which is shown in Fig. 11. It designs of PV panels with IC MPPT technique, boost converter and proposed RS MLI. The conventional MLIs produce more THD which is reduced by utilizing large size filters [16]. The device is increases with increase in no. of levels for conventional inverter, therefore the various investigators work on new topological designs. This paper proposes a 1-phase 7-level RS MLI integrated with PV panels. In which separate DC source of RS MLI is replaced by separate PV panel with IC MPPT technique and boost converter. PV based RS MLI
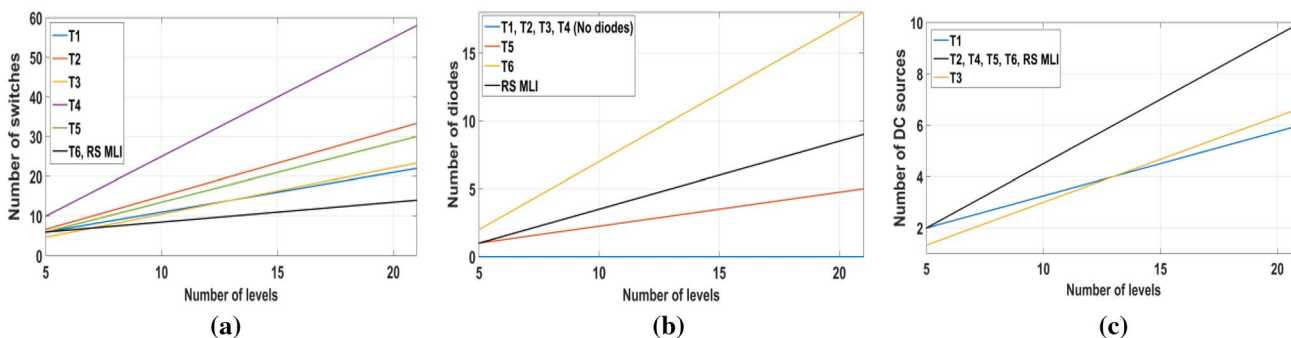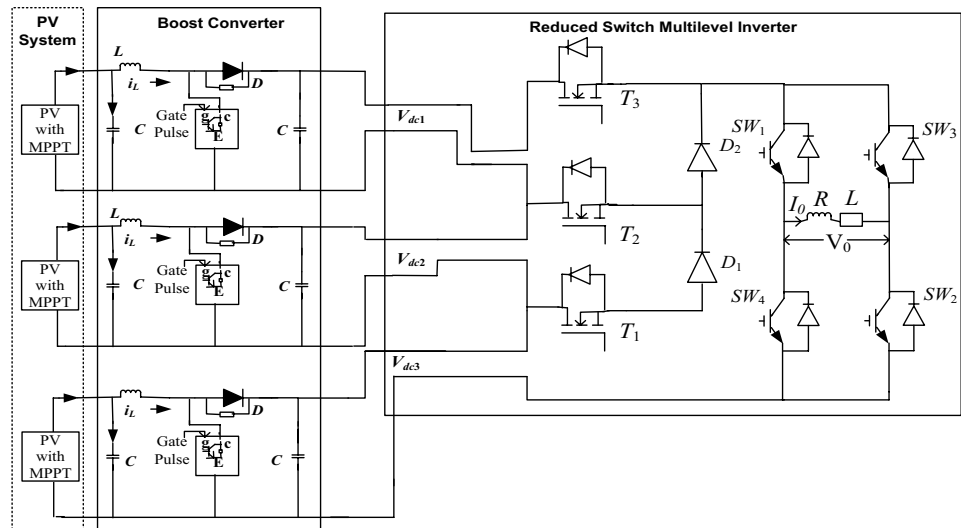

Fig. 10 The proposed RS MLI is compared with several recently developed MLIs topologies **a** No. of required switches against the no. of voltage levels, **b** No. of diodes against no. levels, **c** No. of DC sources against the no. of voltage levels

Fig. 11 1-phase 7-level RS MLI integrated with PV panels with DC–DC boost converter

inverter has gained attention lately for high voltage and high power applications due to numerous advantages such as less no. of devices, improved voltage output quality, less switching losses is and reduced THD.

8 Selected harmonic elimination (SHE) technique

Various types of optimization technique are used for generating the switching angels of MLIs switches. Space-vector-modulation (SVM) and carrier-based-modulation (CBM) technique are the suitable control scheme for high switching frequency. In SVM choosing proper vector is complicated when utilizing more no. of levels [28]. Also, the CBM is the least difficult for execution in equipment. In this paper, SHE technique is used to synthesize the output voltage of MLIs [29]. By taking fourier series analysis, the staircase output voltage of RS MLI with non-equal DC sources can be expressed as mentioned below [6]:

$$V(\omega t) = \sum_{m=1}^{\infty} V_m \sin(n\omega t) \tag{14}$$

where V_m denotes the magnitude of mth harmonic. The even order harmonic components are equal to zero for such quarter-wave symmetrical waves. Therefore Eq. (14) can be extended based on magnitude of each harmonic order as follows. The modified equation of voltage output becomes as:

$$V_m = \begin{cases} \frac{4V_{dc}}{m\pi} \sum_{i=1}^{\infty} K_i \cos(m\alpha_i), & \text{for odd } m \\ 0, & \text{for even } m \end{cases} \tag{15}$$

where K_i is the ratio of V_{dci} to V_{dc} such that $V_{dci} = V_{dc} \times K_i$. For given voltage levels and switching angles, F unknown variables should be solved to settle the equation set. Fundamental component forms the Eq. (14) as indicated in Eq. (16).

$$M = \frac{1}{F}[K_1 \cos \alpha_1 + K_2 \cos \alpha_2 + K_3 \cos \alpha_3 + K_4 \cos \alpha_4 + \cdots + K_L \cos \alpha_L] \tag{16}$$

where M is defined as under: $M = \frac{V_1}{3FVdc/\pi}(0, M < 1)$.

In this work, targeting the 5th and 7th harmonics, the three non-linear equations for the solution of the problem are taken as under:

$$\begin{cases} \frac{1}{3}[K_1(\cos \alpha_1) + K_2 \cos(\alpha_2) + K_3 \cos(\alpha_3)] = M \\ K_1(\cos(5\alpha_1) + K_2 \cos(5\alpha_2) + K_3 \cos(5\alpha_3) = 0 \\ K_1(\cos(7\alpha_1) + K_2 \cos(7\alpha_2) + K_3 \cos(7\alpha_3) = 0 \end{cases} \tag{17}$$

The above non-linear equations are solved targeting elimination of the 5th and 7th order harmonics. The conventional technique such as NR and resultant method are also tried to solve these set of non-linear equations. The NR method is derivative dependent and can stop in local optima. Also a sensible selection of the initial values alone guarantees conversion. By resultant method determination of the switching angles to eliminate lower harmonics,

but this method is not attractive when no. of inverter level increases [28]. In this paper present, GA approach is used to obtain the optimal value of switching angles of PV based 7-level RS MLI, considering the THD an objective function by reducing of 5th and 7th order harmonics at different value of switching angles. The range of switching angles is as under:

$$0 < \alpha_1 < \alpha_2 < a_3 < \frac{\pi}{2} \tag{18}$$

To confirm the superiority of voltage waveform, THD can be calculated as follows

$$\text{Minimizing, } \%THD = \left[\frac{1}{V_1^2} \sum_{K=2}^{\infty} (V_K)^2 \right]^{\frac{1}{2}} \times 100 \tag{19}$$

where V_K is describe the particular voltage harmonics. To determine the fitness function GA is generally process for some iterations (in this paper work 100 iteration chosen). The benefit of GA technique is searching start with randomly and simultaneously handles big amount of data for any no. of MLIs levels.
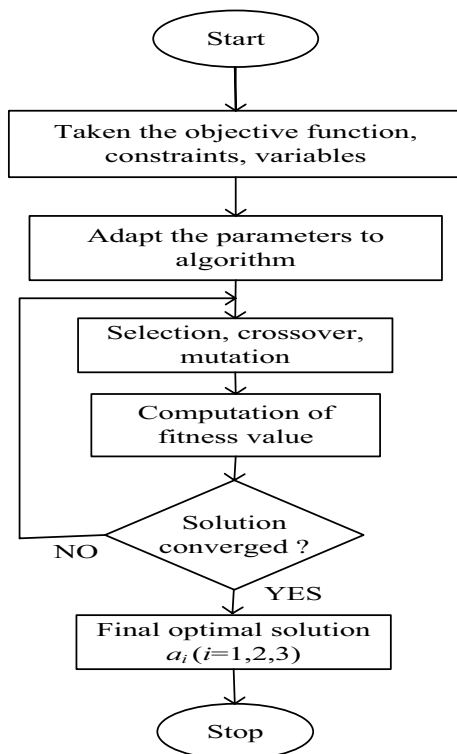

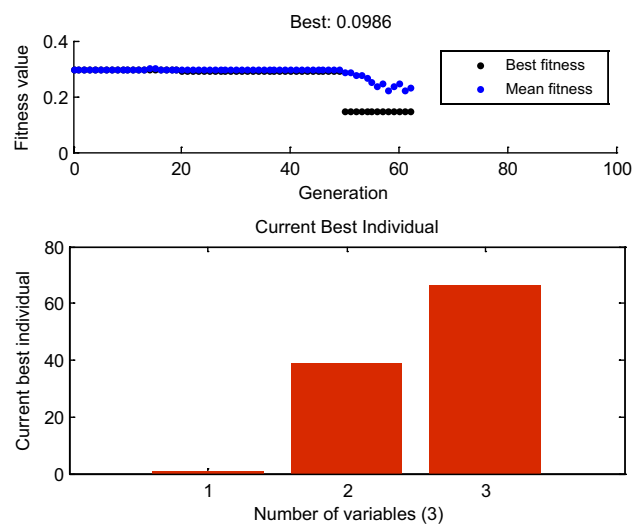**Fig. 12** Genetic algorithm flowchart for 7-level PV based RS MLI

Fig. 13 Results obtained for Best fitness and number of variable from the GA

9 Switching angles calculation by genetic algorithm (GA) using SHE

GA is search machinery which emulates the natural selection and the living organisms of genetics [30]. By quantitative method that solves the problem and has been the most used technique to optimize a function which originates in constrained functions. The operation of GA mainly is divided in three parts such as selection, crossover and mutation. In process, selection rules in selecting the individuals, called parents that contribute to the population to the next generation. In crossover, process, rules in combines two parents to form children for the next generation and in mutation rules apply random changes to individual parents to form children. The flowchart arrangements of the GA is shown is Fig. 12.

The GA toolbox is an inbuilt graphical user interface that allows using GA in MATLAB environment without working at the command line [31]. The results obtained from GA are shown in Fig. 13. The obtained switching angles from genetic algorithm are shown in Table 3. In GA toolbox, user interface at MATLAB software without work for command line and do not required initial guess.

Obtained values for switching angles (in Table 1) satisfy the Eq. (17) for the considered no. of population. In the work of paper switches of RS MLI made by IGBTs and angles of IGBTs apply through pulse generators. Performed simple with require less derivations and systematic appearance for reduction of harmonics as the no. of levels increases. Therefore GA technique is taken for obtain optimal value of switching angles.

	No. of iteration fitness (%)	Switching angles (°)			Mean fitness (%)	Best
Results obtained from (GA)	100	α_1	α_2	α_3	19.22	9.86
		12.56	59.34	62.87		

Table 3 Obtained results from genetic algorithm

Fig. 14 **a** The output voltage of each PV panel without boost converter, **b** output voltage of each PV panel with DC–DC boost converter
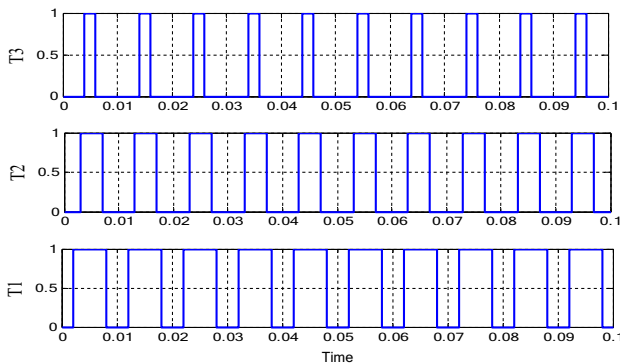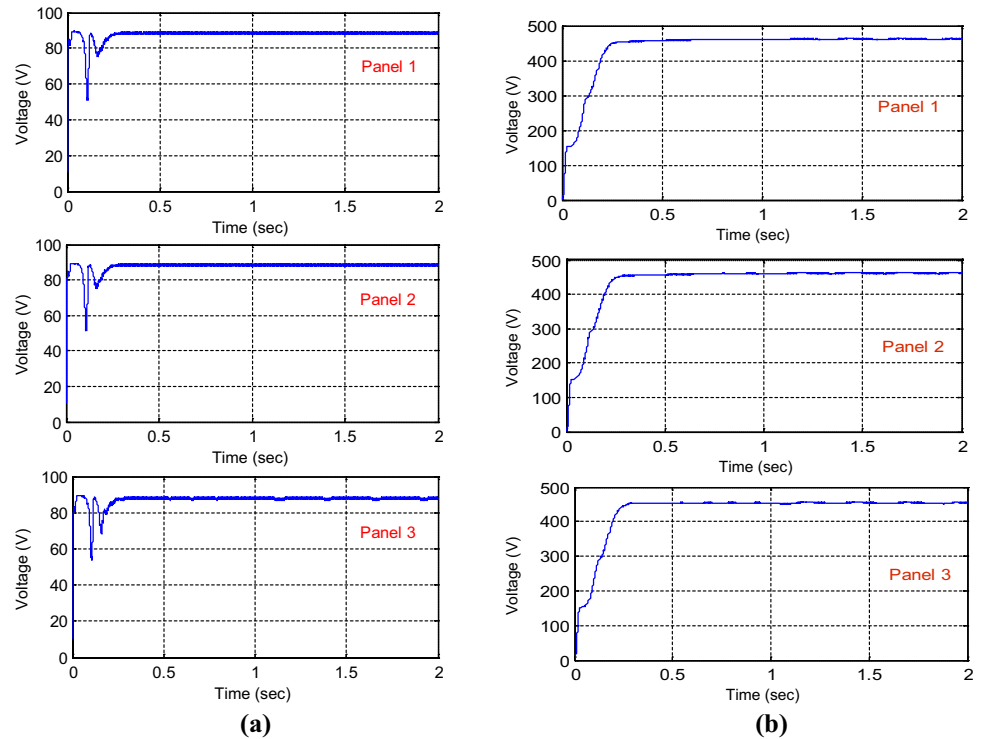

Fig. 15 PWM signals for level generation of RS MLI switches T_1, T_2 and T_3

10 Results and analysis

The work presented in this manuscript is performed on the PV based DC–DC boost converter along with IC MPPT

technique incorporated with RS MLI using MATLAB/SIM-ULINK software. A DC–DC boost converter is an adepter controlling the load power through a regulated duty cycle The proposed system, each PV panel is individually connected to input of RS MLI via separate DC–DC converter with MPPT technique under changing irradiation and temperature. Figure 13a is shows the output voltage and current of PV system without boost converter. According to ADP1612 and ADP1613 have a maximum duty cycle of DC to DC boost converter is 90%. In this paper work three DC to DC converters for each PV panels and optimal duty cycle find out of each converter i.e. converter 1 is 0.811, converter 2 is 0.812 and converter 3 is 0.811. Therefore the output voltage of DC–DC converter is improved from 88 to 450 V approximately for each PV panel shown in Fig. 13b.

The obtained DC–DC boosted output voltage for each PV array is appropriate for network voltage rating. From

Fig. 14b it can examine that the system permanence is stable and produced voltage output is more with less convergence speed. The boosted output voltage of each panel with less oscillation is suitable for 7-level RS MLI.

The proposed 7-level RS MLI switches (IGBTs) are triggered using GA technique, by making use of pulse generater. The required pulse width modulating (PWM) signals for the level generation switches T_1, T_2 and T_3 are shown in Fig. 14 (Fig. 15).

The simulated output voltage obtained from 1-phase 7-level PV RS MLI for R-L load shown in Fig. 16a. The THD present in output voltage is 10.01% at frequency 50 Hz which is shown in Fig. 16b. From Fig. 16b it can be observed that low order harmonics are almost eliminated from PV based RS MLI.

In order to confirm the theoretical and simulation analysis, hardware result of output voltage for 7 level RS MLI shown in Fig. 17. As per the limited rating of DC sources available in laboratory, the value of V_{dc} is maintained at 40 V. Unlike simulation analysis the dc–dc converter and MPPT control are not adapted for experimental testing. However, all the experimental validations have been carried out under a simulation-like environment. The experimental value of resistive load is taken R = 90 Ω for inductive load conduction R = 90, L = 50 mH and load is varied R = 60 Ω, L = 30 mH. HGTG12N60A4 IGBT switches controlled by an Arduino Mega 2560 controller with RGP30J as distinct diodes are used to assemble the power circuit. As per the control plan (low/high switching frequency) necessity and for testing the RS MLI in an industrial environment, fast processing controllers such as field programmable

Fig. 17 Experimental results of 7-level RS MLI **a** voltage output for ▶ high modulation index varying *MI* (y-scale: 60 V/div, x-scale: 8 ms/div) **b** obtained output voltage and current for 7-level with *RL* load (y-scale: 60 V/div, 2 A/div) **c** obtained output voltage and current corresponding harmonic spectra (y-scale: 100 V/div, 2 A/div)

gate array or digital signal processors can be used instead of using an Arduino. TLP250 photocouplers are used to amplify the switching pulses, which also provide necessary isolation between the power and control circuits. Results are recoded using a DSO.

The lower order harmonics components are reduced from the experimental output voltage of RS MLI shown in Fig. 17c. The harmonics components present in experimental output voltage is 10.73%. The proposed RS MLI also operates satisfactorily with varying frequency. The developed RS MLI can be a good solution for integrating it with renewable energy sources and for generating higher voltage steps using the reduced number of switches [11]. So far the performance of the proposed RS MLI for PV application is validated through extensive simulation and experimental analysis followed by detailed of technical design and economic aspects.

11 Conclusion

This paper present 1-ϕ PV based 7-level RS MLI with DC–DC boost converters and IC MPPT technique. The most important feature of PV based RS MLI system is being expedient for increasing the number of output
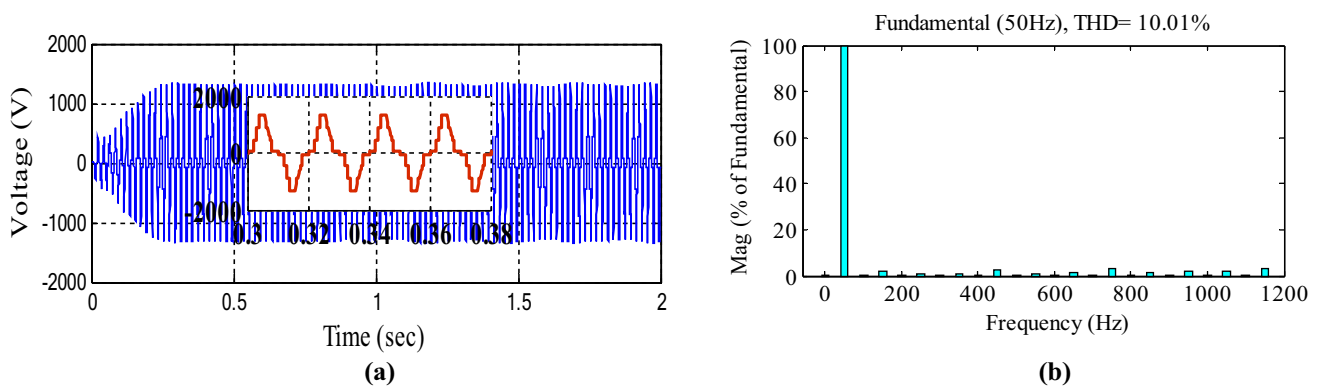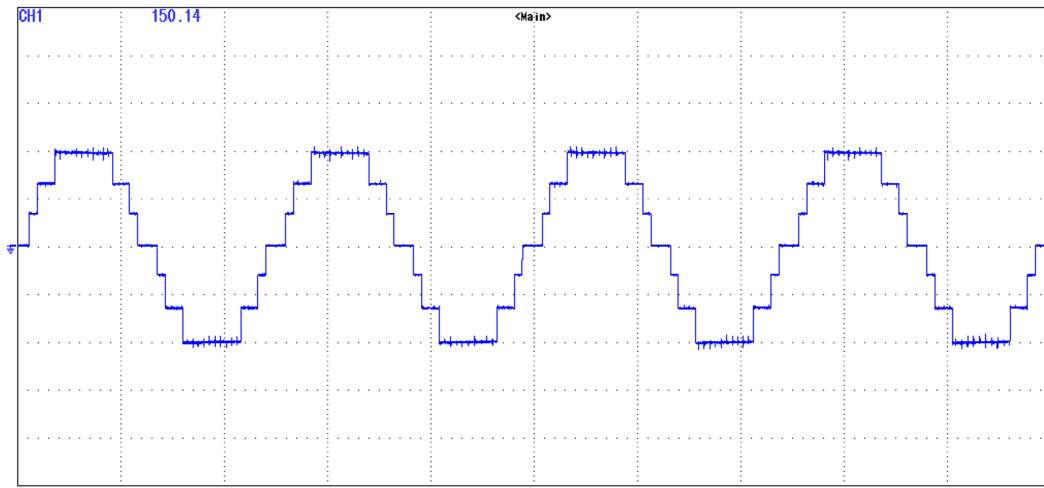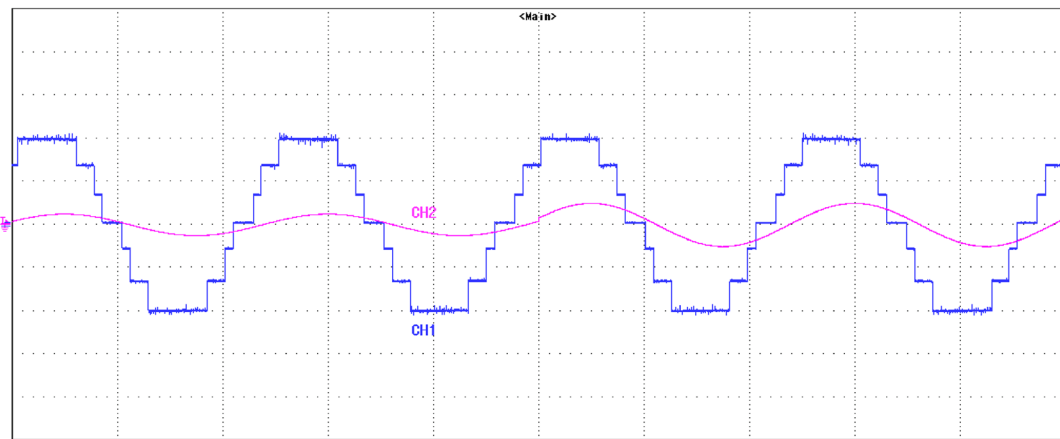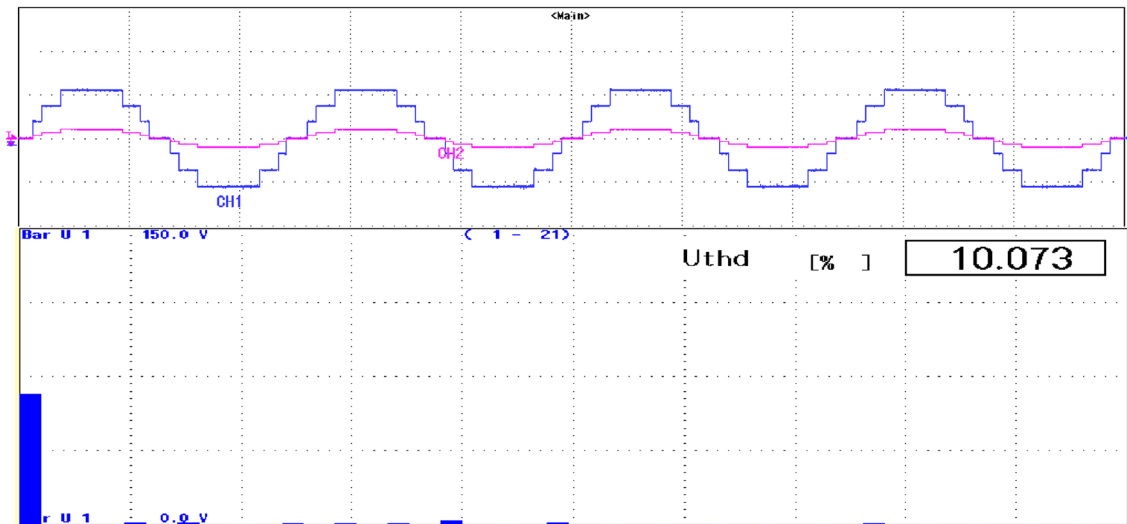

Fig. 16 **a** Output voltage waveform of 7-level PV based RS MLI, **b** FFT analysis of voltage THD outcome of 7-level PV based RS MLI

(a)

(b)

(c)

levels with fewer number of switches, thereby reducing the volume, size and cost of multilevel inverter. The GA based SHE technique is used to control the switching pulses of IGBTs for multilevel inverter. By GA technique optimal switching angles are generated in order to eliminate dominant lower order harmonics. From the results it is observed that GA technique is more effective in reduction of THD at the voltage output of PV based RS MLI. In this work, 100 iterations are selected at GA toolbox for obtaining the optimal values of switching angles. The developed topology is investigated through several MATLAB simulations as well as experimental tests in the laboratory applying the modified control approach. In the future work, the proposed PV based RS MLI compare with conventional cascaded H-Bridge MLI in terms of THD analysis of output voltage.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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